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Design and fabrication of a novel MEMS thermoelectric generator

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Abstract

A thermoelectric microgenerator based on a novel structure, in which the heat flowing in elements with different thermal resistances produces local temperature differences in the device, has been designed, fabricated in BESOI technology and experimentally characterized. The temperature differences in the microgenerator are converted into a voltage by means of the Seebeck effect exploiting planar thermocouples.

Keywords: Thermoelectric generators; Micromachining; Seebeck effect; Energy Harvesting.

1. Introduction

In order to improve the power density per unit area in thermoelectric generators (TEGs), different examples of miniaturized TEGs have been developed and proposed in the literature both in thin film and micromachining technologies [1-4]. The miniaturization of TEGs is very promising because a high number of thermocouples can be integrated in a small area, with a potential increase in generated voltage at low temperature difference. One approach in the design of miniaturized thermoelectric devices is to scale down macroscopic Peltier cells. In this case, vertical pillars of thermoelectric materials are arranged and electrically connected in series and thermally sandwiched in parallel between two substrates. Typically, the micromachined thermogenerators are fabricated by means of non-standard techniques specifically developed to allow the fabrication of three-dimensional structures for the building blocks of thermocouples. It may also

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be necessary to use post-processing techniques to assemble the various elements that compose the microgenerators [1-3]. Another approach in miniaturization of thermoelectric generators is the adoption of membrane-based thermopiles, which are used for sensing applications; in this case the pillars of thermocouples are substituted with planar elements [4-5].

2. Design and fabrication of micromachined thermoelectric generator

In order to avoid the use of non-standard micromachining technology in the attempt to overcome the difficulties to apply or maintain temperature differences over time in micromachined devices, owing to the low thermal resistance and capacity of the microstructures, a novel configuration of micromachined TEG has been proposed using readily available MEMS technologies.

Fig. 1 (a) shows the basic structure of the proposed TEG based on a suspended membrane with a central hole. If the device is placed on a hot surface at temperature T_B, the heat Q flows into the device and due to different thermal resistance paths, i.e. silicon membrane and silicon frame, local temperature differences are created. These internal temperature differences are converted into a voltage by means of the Seebeck effect, utilizing planar thermocouples.

The miniaturized TEG has been designed using BESOI (Bonded and Etched-back Silicon On Insulator) technology available at the CNM (Centro Nacional de Microelectrónica), Barcelona (Spain). Instead of the three-dimensional structures typically used to fabricate thermoelectric elements in thermogenerators, planar thermocouples have been made up of thin layers of *p*-type polysilicon and a metal alloy of aluminium and copper. In this way the Seebeck coefficient of a thermocouple results of about 100 μV/K [6].

Fig. 1 (b) shows a 3D schematic of the micromachined thermoelectric generator. The die dimensions are 7 × 7 mm^2. The device consists of a squared silicon membrane with sizes 6 × 6 mm^2 and 15 μm thickness. The silicon frame has a thickness of 450 μm. A square hole in the chip membrane, with size 500 × 500 μm^2, can be utilized to improve the heat transfer between the thermogenerator and the ambient by means of the resulting airflow.

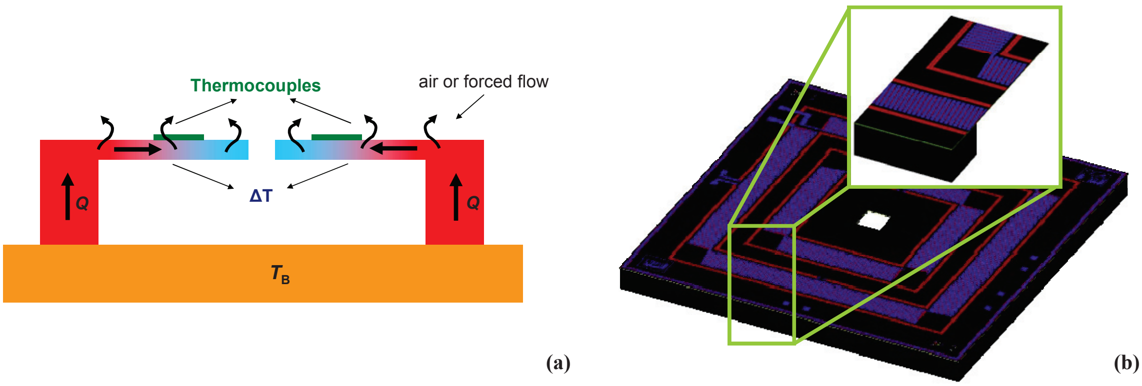

Fig. 1. Simplified cross-section of the proposed device with suspended membrane and central hole (a). 3D schematic of the designed micromachined generator (b).

As depicted in the top-view schematic of Fig. 2 (a), the device consists of two thermopile arrays: the external array is formed by 300 thermocouples connected in series, whereas the internal array consists of 160 thermocouples.

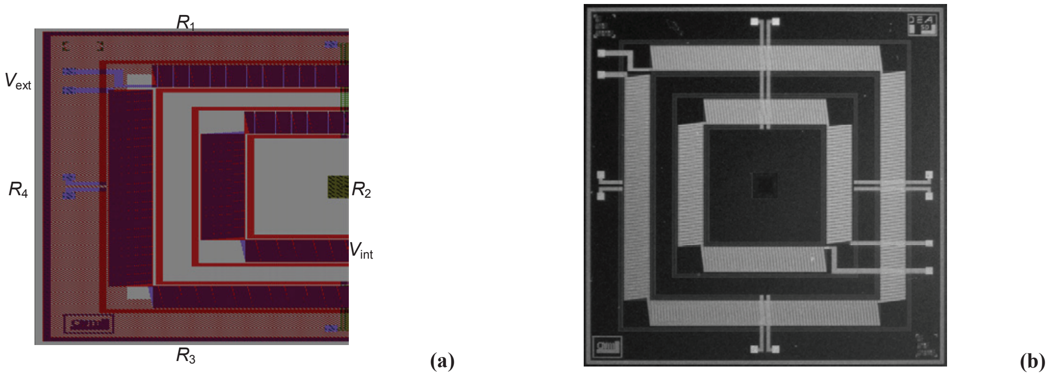

Fig. 2. Top-view schematic of the designed thermoelectric microgenerator (a). Picture of the fabricated micromachined TEG (b).

3. Experimental results and discussion

Finite element simulations have been carried out using the *Comsol Multiphysics* software to analyze the behavior of the thermoelectric generator. Fig. 3 (a) shows the simulated results of the temperature distribution for the microgenerator with a uniform temperature of the bottom side $T_B = 80$ °C, while the ambient temperature has been set at 25 °C.

The fabricated micromachined TEG has been experimentally characterized as a function of the temperature T_B applied at the chip bottom by means of an experimental set-up including a Peltier cell and a reference Pt100 temperature sensor to drive and monitor temperature, and a PC-based acquisition system.

Experimental results reported in Fig. 3 (b) show that, by placing the device on a hot surface, temperature gradients are present inside the device, providing an output voltage of about −180 µV and −400 µV in the case of a bottom side temperature T_B of 10 °C for the internal and external thermocouples arrays, respectively, and about 340 µV and 900 µV in the case of a temperature T_B of about 50 °C.

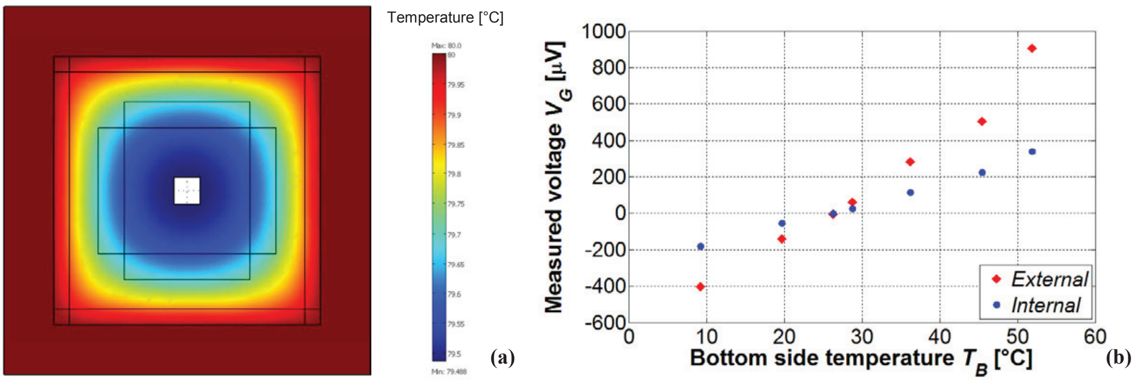

Fig. 3. Simulated results of the temperature distribution for the microgenerator with a uniform temperature of the bottom side $T_B = 80$ °C and ambient temperature at 25 °C (a). Measured output voltage versus the applied bottom side temperature T_B.

Due to the novel structure and conversion principle of the proposed microgenerator, it is not possible to directly compare the performance of the fabricated device with the micromachined thermogenerators reported in literature, because they are typically characterized applying a temperature difference, in contrast to the developed device which has been characterized as a function of the temperature on the bottom side.

However, it is possible to attempt a comparison by considering for the designed microgenerator an equivalent thermal gradient given by the difference between the bottom side temperature T_B and the room temperature. The performances of the proposed device are reported in Table 1 where R_{in} represents the internal electrical resistance, $P_{L,max}/\Delta T^2$ is the output power in matched-load conditions per unit squared temperature difference, and *PF* represents the power factor, which is defined as the power in matched-load conditions per unit squared temperature difference and per unit thermogenerator area.

Table 1. Performance of the fabricated micromachined TEG.

	R_{in} [kΩ]	$P_{L,max}/\Delta T^2$ [μW/K²]	*PF* [μWmm²/K²]
Internal array	8	$4.5\ \ 10^{-9}$	$9.2\ \ 10^{-11}$
External array	20	$1.1\ \ 10^{-8}$	$2.1\ \ 10^{-10}$

The experimental results are in agreement with values recently reported in the literature for membrane-based micromachined TEGs [5].

4. Conclusions

A thermoelectric microgenerator based on a novel device configuration has been designed, fabricated and experimentally characterized. The thermoelectric generator provides an output voltage of about 900 μV and 340 μV, respectively, for the internal and external thermocouples arrays in the case of a bottom side temperature of about 50 °C. Despite the low generated voltages in the present version, the experimental results confirm the feasibility of fabricated thermoelectric device with standard MEMS technology

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